Indian J Phys **75B** (3), 223–225 (2001)

I J P B
— an international journal

Calculation of base transit time in Si HBTs with incorporation of C in SiGe base

Abhijit Biswas and P K Basu*

Institute of Radio Physics and Electronics, University of Calcutta, 92 Acharya Prafulla Chandra Road, Kolkata-700 009, India

E-mail pkbasu@cucc ernet in

Abstract A generalized analytical expression for the calculation of base transit time, τ_b, for Si HBTs with the $Si_{1-x-y}Ge_xC_y$ base has been derived for small amounts of substitutional C. It is observed that τ_b becomes smallest for triangular material (Ge and C) profiles as compared to box-like and trapezoidal profiles. The problems of B outdiffusion and of lattice mismatch in a SiGe base can be mitigated by incorporating C in the SiGe base. Our calculation shows that for the same value of strain between Si and SiGe and between Si and SiGeC, the latter device yields the smallest value of τ_b.

Keywords Base transit time, heterojunction bipolar transistor, SiGeC base

PACS Nos. 85.30.Pq, 85.30.De

1. Introduction

Recently, $Si/Si_{1-x-y}Ge_xC_y/Si$ material systems are finding increasing applications in heterostructure devices as they eliminate the following two problems encountered in Si/SiGe systems. Firstly, in Si/SiGe devices, B outdiffusion across the emitter-base and collector-base junctions deteriorates device performance and secondly, the lattice mismatch between Si and Ge in the SiGe base prevents fabrication of a triangular Ge profile because of poor film stability. Incorporation of C increases the bandgap of a SiGeC base in Si/SiGeC/Si Heterojunction Bipolar Transistors (HBTs) by 26 meV/%C [1] keeping the same amount of Ge and it has a stronger effect on reducing strain than on increasing the bandgap. Calculation of the base transit time for SiGe devices have been reported in several papers [2, 3] in which metallurgical base width, instead of neutral base width, was taken into account. Furthermore, in all these work the variation of saturation-drift velocity on Ge mole fraction has not been considered at all. The first assumption overestimated and the second assumption underestimated the values of base transit time. When both are added, the total transit time becomes closer to the experimental or simulation result. The work reported in the present paper, is free from these assumptions. We report, for the first time, a realistic calculation of the base transit time, τ_b, in a Si/SiGeC/Si N^+-p-N HBT. For different Ge contents in the SiGe base, the calculated values of τ_b, using our model, show good agreement with the reported values [4] obtained from the Energy Balance (EB) simulator.

2. Theory

We consider a N^+-p-N HBT, having a $Si_{1-x-y}Ge_xC_y$ base in which the Ge and C profiles are assumed to be box-like, trapezoidal and triangular. The reduction of the base bandgap due to heavy base doping concentration $N_A(z)$, incorporation of Ge and C is 18 ln $(N_A(z)/10^{17})$ meV, 8.25 meV/% [Ge] [5] and –26 meV/%[C], [1] respectively, for a strained SiGeC base layer. $N_A(z)$ denotes the base doping profile which is described by rising and falling exponentials having a peak concentration N_{bm} occurring at $z = R_p$, N_{be} and N_{bc} denote, respectively, the emitter-base and the collector-base doping concentrations. We employ the same diffusion constant model for $Si_{1-x-y}Ge_xC_y$ with a small amount of C as used in SiGe [3]. Thus

$$D_{n,\mathrm{SiGeC}}(z) = (1 + Ky_{tot})\, D_{n,\mathrm{Si}}(z), \qquad (1)$$

where $K = 3$, y_{tot} is the total Ge content in the base. $D_{n,\mathrm{Si}}(z)$ and $D_{n,\mathrm{SiGeC}}(z)$ are the diffusion constants of electrons in Si

*Corresponding Author

and SiGeC bases, respectively. $D_{n,\mathrm{Si}}(z)$ can be empirically fitted [3] as

$$D_{n,\mathrm{Si}}(z) = MN_A^{-n}(z), \tag{2}$$

where $M = 2.86 \times 10^8$ cm$^{-0.74}$ s^{-1} and $n = 0.42$ for electrons.

The base transit time $\tau_b^*{}_{,\mathrm{SiGeC}}$ of a SiGeC HBT can be written as [6]

$$\tau^*_{b,\mathrm{SiGeC}} = \int_{Z_l}^{W_b} \frac{n^2_{i,\mathrm{SiGeC}}(z)}{N_A(z)} \left[\int_z^{} \frac{N_A(x)dx}{D_{n,\mathrm{SiGeC}}(x) n^2_{i,\mathrm{SiGeC}}(x)} \right] dz \tag{3}$$

In Eq. (3), Z_l and W_b are the edges of the depletion regions of the emitter-base and the collector-base junctions, both in the base. n_{ib} is the intrinsic carrier concentration in the SiGeC base given by [3]

$n_{ib}^2(z) = \gamma n_{i0,\mathrm{Si}}^2 \exp[\Delta E_{g,\mathrm{eff}}/k_B T]$ where $\Delta E_{g,\mathrm{eff}}$ is the effective bandgap narrowing which includes the bandgap narrowing due to incorporation of Ge and C and the same due to heavy base doping concentration.

Due to carrier velocity saturation in the collector-base depletion region the electron concentration in the base increases and this introduces an additional term in the base transit time expression which is given by [7]

$$\tau^v_{b,\mathrm{SiGeC}} = \int_{}^{W_b} \frac{N_A(W_b) n^2_{i,\mathrm{SiGeC}}(z)}{v_s(z) N_A(W_b) n^2_{i,\mathrm{SiGeC}}(z)} dz \tag{4}$$

where $v_s(z)$ is the electron saturation velocity which varies with x, the mole fraction of Ge, as [8]

$$v_s(z) = 0.97 \times 10^7 \exp(-2.53203x) \text{ cm/s}. \tag{5}$$

The total base transit time is then given by

$$\tau_{b,\mathrm{SiGeC}} = \tau^*_{b,\mathrm{SiGeC}} + \tau^v_{b,\mathrm{SiGeC}}. \tag{6}$$

3. Results and discussion

Figure 1 shows the material (Ge and C) profiles in the SiGeC base of a N$^+$-p-N transistor with metallurgical base width W_{BM}. Figure 2 gives the variation of base transit time τ_b with $\omega = Z_T/W_{BM}$. For a fixed amount of Ge and C contents τ_b decreases gradually with increasing ω and the maximum and minimum values of τ_b occur respectively at $\omega = 0$ and $\omega = 1$. The material profiles are box-like when $\omega = 0$; with increasing ω the length of the base region over which a drift field exists, widens to accelerate the minority carriers thereby decreasing the transit time. When $\omega = 1$, signifying triangular material profiles, the drift field region covers the entire base width and the transit time attains the minimum value. For the same amount of strain between Si, $Si_{0.9}Ge_{0.1}$ and between Si, $Si_{0.871}Ge_{0.126}C_{0.003}$, the latter device yields a lower τ_b as C has greater ability to reduce the strain than to increase the bandgap. The variation of τ_b for a HBT of 90 nm base width with triangular Ge and C profiles is displayed in Figure 3 as a surface. The plot shows that τ_b attains the smallest value for 10% of Ge and 0% of C in absence of B outdiffusion. But in practice, this minimum value cannot be achieved without C as it prevents B outdiffusion. The calculated values of τ_b, using our model,

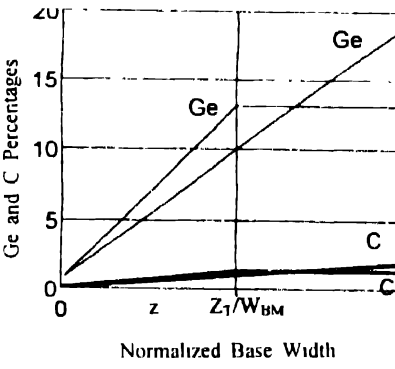

Figure 1. Trapeziodal and triangular material (Ge and C) profiles in the base of a Si/SiGeC/Si HBT

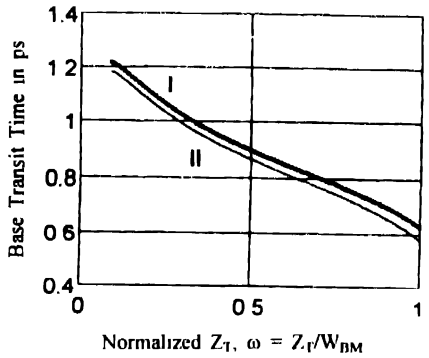

Figure 2. Base transit time *versus* ω (= Z_T/W_{BM}) for exponential base doping profiles occurring at $R_p = 27$ nm with $W_{BM} = 90$ nm, $N_{bm} = 4 \times 10^{18}$ cm^{-3}, $N_{bc} = 2.8 \times 10^{18}$ cm^{-3} and $N_{bc} = 1 \times 10^{17}$ cm^{-3} at $T = 300$ K for (I) $Si_{0.871}Ge_{0.126}C_{0.003}$ base and (II) $Si_{0.9}Ge_{0.1}$ base

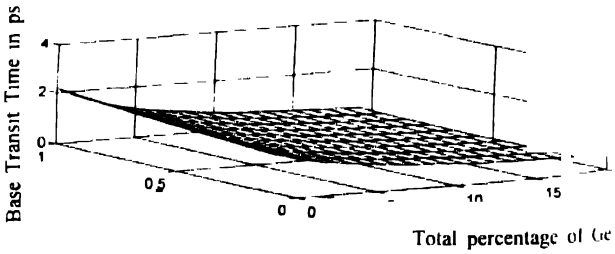

Figure 3. Variation of τ_b with total percentages of Ge and C content for a SiGeC base HBT having triangular Ge and C profiles with other parameters same as in Figure 2

for $Si/Si_{1-x}Ge_x/Si$ HBTs used in [4] are 0.36 ps, 0.40 ps, 0.49 ps and 0.63 ps for 10%, 15%, 20% and 25% of Ge contents, respectively. The corresponding values using the Energy Balance simulator are 0.5 ps, 0.53 ps, 0.6 ps and 0.71 ps, respectively [4]. Our results show good agreement with the published simulation results [4] and thus the agreement ensures the validity of our model.

3. Conclusion

The triangular material (Ge and C) profiles in the base gives smallest value of τ_b. With the incorporation of substitutional C in SiGe base, triangular Ge profile can be used in the base without deteriorating the film stability and device performance and thereby smallest possible value of τ_b can be obtained for small amounts of C. Incorporation of small amounts of C ($\lesssim$1%) in SiGe base improves the performance of the SiGe material eliminating B outdiffusion.

Acknowledgment

The authors are thankful to Prof. C K Maiti, IIT, Kharagpur, India, for calling our attention to some useful references.

References

[1] L D Lanzerotti *et al IEEE Electron Device Lett* **17** 334 (1996)

[2] D M Richey, J D Cressler and A J Joseph *IEEE Trans. Electron Devices* **44** 431 (1997)

[3] V S Patri and M J Kumar *IEEE Trans Electron Devices* **45** 1725 (1998)

[4] B Senapati, C K Maiti and N B Chukrabarti *Int Conf VLSI Design (Jan 2000, Calcutta)* p 488 (2000)

[5] S S Iyer *et al IEEE Trans Electron Devices* **36** 2043 (1989)

[6] H Kroemer *Solid State Electronics* **28** 1101 (1985)

[7] K Suzuki and N Nayakam *IEEE Trans Electron Devices* **39** 623 (1992)

[8] F M Bufler *et al IEEE Electron Device Lett* **18** 264 (1997)